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Architectural Acoustics

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FOREWORD

WITH the growing appreciation of both the possibility and the necessity of producing comfortable conditions of hearing in any auditorium, more and more attention has been given by designers, builders and owners to the problem of architectural acoustics.

Realizing this fact and the importance of the researches of Prof. Sabine of Harvard University in establishing the subject on a true scientific basis, we undertook as long ago as 1911, to enlarge our service to the architectural profession by making the results of these researches available in a practical and commercial form. Until his recent death, Prof. Sabine was retained by us in a consulting capacity, with active assistance from Mr. Clifford M. Swan, formerly on the staff of the Physics Department of the Massachusetts Institute of Technology, who was for many years closely associated with Prof. Sabine and who was, in fact, his only student in the subject. Mr. Swan is now continuing the work of Prof. Sabine and we have arranged to have Mr. Swan's counsel and advice, as formerly.

Thus with the best expert assistance, and with the new materials and the perfected methods that we have developed during the past ten years, we are able to offer our clients the benefits of the latest scientific acoustical discoveries, together with a technique of construction acquired through wide and varied experience in this type of work.

Federal Court Room, Indianapolis
Rankin, Kellogg & Crane, Philadelphia, Architects
Johns-Manville Acoustical Correction installed in wall and ceiling panels

In the following article Mr. Swan presents a brief discussion of the subject of architectural acoustics, outlining the principal problems which are encountered and the lines along which they are properly solved. We have added a number of illustrations showing some of the buildings in which we have installed acoustical treatment.

This book is presented to architects with our compliments, in the hope that in it they may find the possibility of solution of many acoustical problems. Our services are always at their disposal without fee for examinations and reports, and we are ready to furnish estimates and to execute corrective work promptly and efficiently in any section of the country.

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CLIFFORD M. SWAN, S.B., A.M.

OF THE many technical problems with which an architect is from time to time confronted, not the least important is that of architectural acoustics. In churches, courtrooms, lecture halls, and the great auditoriums of monumental buildings, it ranks equal in importance with lighting, heating and ventilation. Strange to say, only within the past twenty years has there been developed a definite science applicable to the design and construction of buildings, as well as effective materials for correction and a technique of their installation.

It is remarkable that in no other field of technical knowledge have antiquated ideas yielded so slowly to oft-repeated experience. At last, however, through the results of scientific investigation, the useless stringing of wires is being discontinued, while the sounding-board, moderately useful at times, is not now considered an universal panacea, and simple ratio between length, breadth and height is no longer looked upon as an adequate basis for acoustical design.

Broadly, the subject of architectural acoustics may be divided into two parts: The transmission of sound through floors, walls, or other partitions into rooms situated apart from the source; and the phenomena arising within a given room or auditorium due entirely to factors of interior design and finish as affecting

House of Representatives, Missouri State Capitol, Jefferson City
Tracy & Swartwout, New York City, Architects
Johns-Manville Acoustical Correction installed behind draperies, and on ceiling

sound, either generated within the room or entering from without.

SOUND TRANSMISSION

The first of these divisions, that of sound transmission, is but just beginning to receive scientific attention, and the amount of reliable data at hand is small. The problem of deadening walls or floors is quite as much a question of construction as of deafening materials. The importance of the former element has not been appreciated, while even in the case of materials themselves, trustworthy figures are lacking as to their efficiency.

The common practice in the past seems to have been to design a material with especial reference to its heat insulating qualities and then arbitrarily to assume corresponding proper-

United States Court of Appeals, Denver
Tracy & Swartwout, New York City, Architects
Johns-Manville Acoustical Correction installed behind wall draperies

ties for sound insulation, an assumption wholly unjustifiable both in theory and practice. Such success as may have been attained in actual installations is to be attributed to practical experience in work of this character which has shown some of the pitfalls to be avoided, rather than to definite and exact information. In the present state of the subject, no one can predict with assurance the degree of efficiency to be obtained from any given form of construction or material. Research is however, progressing along these lines, and the time is doubtless not far distant when at least the principal factors in the problem will be capable of analysis.

AUDITORIUM ACOUSTICS

In marked contrast to the uncertainty surrounding the transmission problem, is the definiteness attaching to the other great

Waiting Room, Southern Pacific Railroad, Oakland, California
Jarvis Hunt, Chicago, Architect
Johns-Manville Acoustical Correction installed in wall and ceiling panels

division of architectural acoustics, that of the so-called internal acoustics of an auditorium. In this field, much careful scientific investigation has been done, notably by the late Prof. Wallace C. Sabine, of Harvard University, which merits thoughtful consideration by all designers or owners of large auditoriums. Sabine's researches have been published from time to time in the architectural and engineering press and have been supplemented by the work of Jaeger and others. They form the basis of all modern practice. The result has been to make possible not only the correction of existent auditoriums but also the design and construction of new ones in a manner such as to obviate all difficulties from the outset.

While much of the success to be attained in this direction must of necessity be a matter of expert consideration and advice,

Music Building, Harvard University, Cambridge
Howells & Stokes, New York City, Architects
Johns-Manville Acoustical Correction installed in wall panels

on account of the complexity and inter-relation of the various phenomena involved, yet the various factors entering into the problem should be a matter of common knowledge in order that there may be a due realization of their importance and possibilities of control.

The phenomena influencing the acoustics of an auditorium may be classified under the heads of reverberation, echo, resonance, and interference, and these must be studied with regard to their effects upon the distinctness and loudness of speech, and the tonal quality of music. As is to be expected, they are not entirely independent one of another; nor are they wholly unmitigated evils in themselves, their presence to a limited extent often being necessary and desirable if not carried to an extreme. The essential factors which influence and control

Pool, Ida Noyes Gymnasium, University of Chicago, Chicago
Coolidge & Hodgdon, Chicago, Architects
Johns-Manville Acoustical Correction installed in ceiling panels

them are the size and shape of the chamber, the contour of the interior surfaces, the nature of the construction and finish, the amount and kind of furnishing and the number of persons present, in so far as these factors affect the reflection, diffraction, and absorption of sound. Refraction, caused by currents of air of different densities arising from the heating and ventilating, may conceivably become a factor, but has been shown to be negligible under almost all circumstances.

REVERBERATION

The most common source of trouble is reverberation, more so today than formerly, owing to modern fireproof construction. In the technical sense, reverberation signifies the prolongation of a sound by its multiple reflection from surface to sur-

Fourth Church of Christ, Scientist, Cleveland
Briggs & Nelson, Cleveland, Architects
Johns-Manville Acoustical Correction installed in wall, cove and ceiling panels

face before its energy is sufficiently absorbed to become inaudible. Since the average sound must be reduced approximately to one-millionth of its original intensity before it reaches the limit of audibility, and since such a sound once produced in a bare room loses but from 2 to 4 per cent. of its energy at each reflection, it is evident that such a sound must be reflected several hundred times before it becomes inaudible. Since this process consumes time, owing to the finite velocity of propagation, the sound is prolonged for a period of several seconds after the original source has ceased to emit energy.

The period of reverberation is evidently inversely proportional to the absorbing power of the room, and directly proportional to the size, since the distance traveled by the sound wave

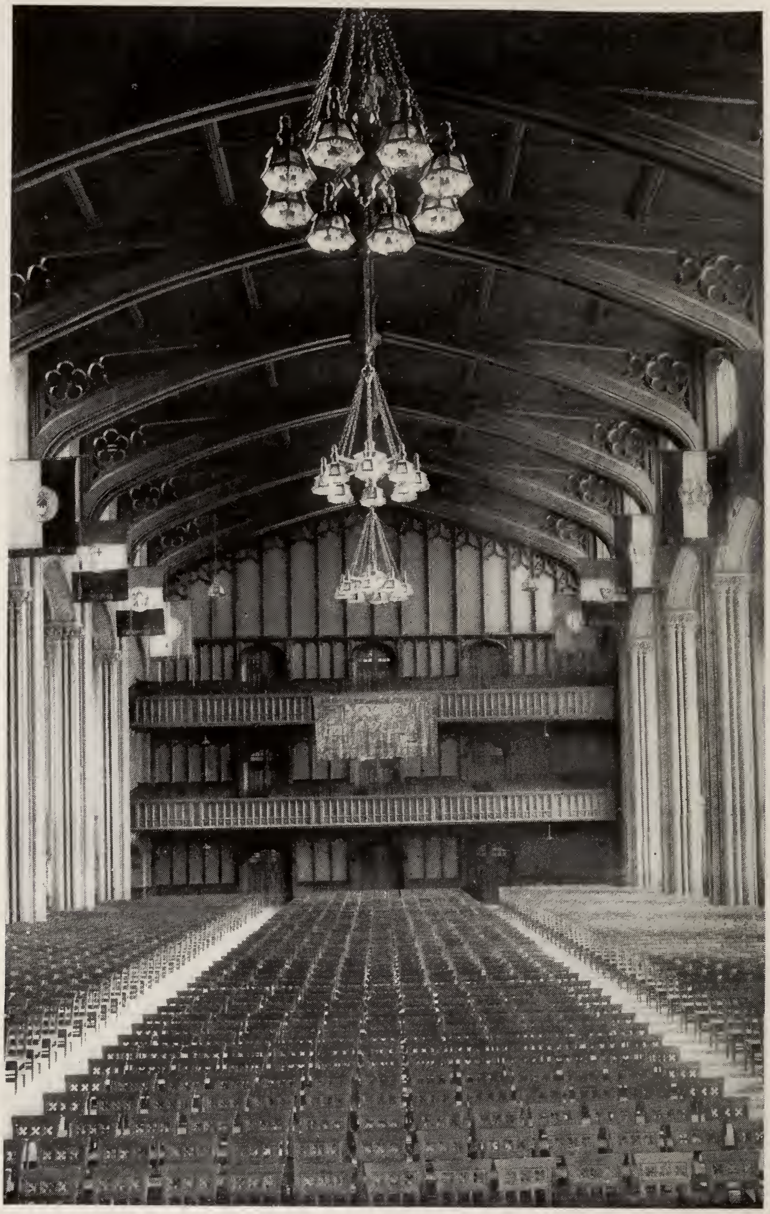
Chapel of the Intercession, New York City
Cram, Goodhue & Ferguson, New York City, Architects
Johns-Manville Acoustical Correction installed in ceiling panels

Fourth Presbyterian Church, Chicago
Cram, Goodhue & Ferguson, Boston, Architects, Howard Shaw, Chicago, Assoc. Architect
Johns-Manville Acoustical Correction installed in ceiling panels

between reflections is greater the larger the room. Its effect, if present in excessive amount, is, as noted, to prolong every sound to such an extent as to cause an overlapping and blurring which is especially distressing in the case of speech. For this reason, in an auditorium intended for speaking alone, it should be reduced as far as is consistent with the carrying power of the sound. It is important to bear in mind, however, that as the reverberation is reduced, the loudness is diminished in very nearly the same ratio, so that there is necessarily a limit to the amount of permissible absorption. In the case of an auditorium used for music, a greater amount of reverberation is desirable than in one used for speaking only, in order that the overtones may not be obliterated (high pitches being more readily absorbed than low) and the quality of tone destroyed. The time of decay of a sound can be calculated with a considerable degree of precision, and the proper design or treatment laid out which will reduce the reverberation to the amount best suited for the room under consideration.

The amount of reverberation can be controlled in various ways. As already shown, it decreases with the size and height of the room, other factors remaining constant. It is also diminished by the presence of recesses or balconies designed to hold a number of people or heavily upholstered seats. Draperies, carpets, furniture, and upholstery are all effective in proportion to their absorbing power, lined and heavy materials being naturally much more efficient than light and thin ones. The clothing of an audience is an important factor, being nearly totally absorptive of sound, and many an auditorium which is exceedingly bad when empty is entirely satisfactory when filled with people. Oftentimes, architectural or other considerations limit the design or furnishings so that a correct condition is not attained, no matter what the number in attendance. Under such circumstances, recourse must be had to a modification of the materials used as an interior finish.

Amasa Stone Chapel, Western Reserve University, Cleveland
Henry Vaughan, Boston, Architect
Johns-Manville Acoustical Correction installed in ceiling panels



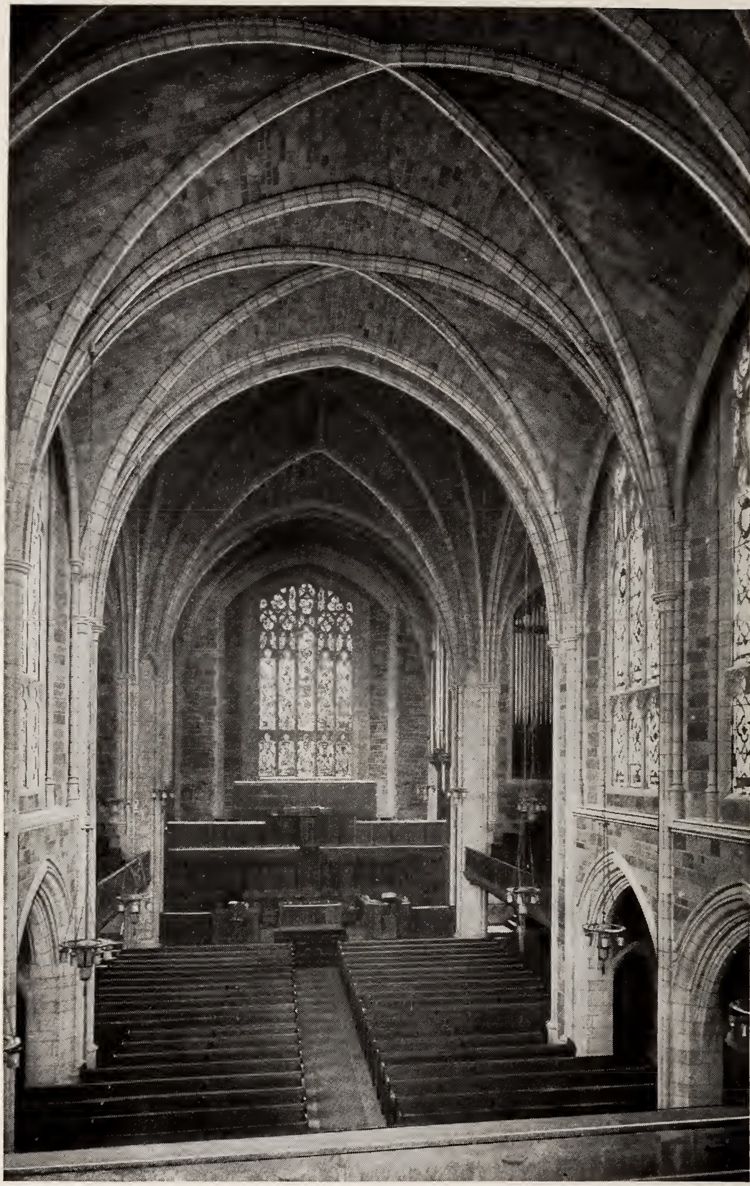
Great Hall, College of the City of New York, New York City
George B. Post & Sons, New York City, Architects
Johns-Manville Acoustical Correction installed in ceiling and rear wall panels

The most common method of producing a sufficient degree of absorption is to place upon portions of the walls or ceiling a certain amount of felt of an extent so chosen as to provide the requisite absorbing power for sound. There are various kinds of felt on the market, but of these, two have been found to be especially suited to this class of work. One is a yellow jute felt such as is used for saddle lining, and the other is a special type of hair felt with gauze reenforcement and freed from the usual impurities found in cattle hair.* Both of these materials are efficient absorbers of sound. As in all substances, the degree of absorption varies with the pitch of the sound. Both grades carry a low percentage of oil, are durable, vermin-proof and non-inflammable, a combination of qualities in conjunction with their high absorbing power which is not to be found in most other felt and which, therefore, renders them particularly suitable for acoustical requirements.

Such surfaces as receive the felt treatment must afterward be covered and protected with a decorative fabric or membrane, and this fabric must be chosen with care in order that it may not too greatly detract from the absorbing power of the felt beneath. The use of a painted membrane or simply a dyed cloth is an important question, as the absorbing power of the treatment depends on this factor both in absolute amount and variation with the pitch. Ordinary paints diminish the absorption considerably but special fabric coatings† have been devised which affect it only to a slight extent. In many cases, beautiful effects can be obtained by covering the felt with tapestry hangings or painted cloth panels of similar design, such as were used in the Little Theatre of New York and the great hall of the Harvard Club of Boston. In all cases the form and

* This material is Johns-Manville Akoustikos Felt used by our company in all acoustical correction work.

† Johns-Manville Akousto-Lite Fabric Coating.



First Congregational Church, Montclair, N. J.
Bertram Grosvenor Goodhue, New York City, Architect
Rumford Tile used as finish on walls and vaults
Constructed by R. Guastavino Co., New York City

manner of decoration must be studied with relation to the architectural and acoustical requirements of the individual problem.

The location of treatment with such absorbing materials is of prime importance, not only because their efficiency in reducing reverberation depends on their receiving the major portion of the reflected waves of sound, but also on account of certain phenomena of localized effect to be discussed presently. A careful study is, therefore, necessary in all cases to determine the extent and location of those areas best suited to an effective treatment, both from an acoustical and an architectural standpoint.

An important contribution has recently been made to acoustical science in the development of two patented materials of structural character suitable for the interior finish of new buildings and having a high degree of absorption comparable in efficiency to felt of equal thickness. One is a ceramic tile* and the other is an artificial stone.† Both are manufactured in such a way as to produce intercommunicating pores of uniform size which give the maximum sound absorption. These materials are not plastic, but must be moulded and set in mortar as a masonry finish. They are especially adapted to tile arch construction, and on account of their combination of acoustical, fireproof, and structural qualities furnish new and useful possibilities in architectural design and construction.

SOUNDING BOARDS

The question is sometimes asked as to the value of a sounding-board in improving acoustical conditions. Such a device, if properly designed and placed, causes a slight reduction in the amount of reverberation when a speaker stands beneath it, as it casts a certain amount of sound shadow on the ceiling, thus con-

* "Rumford Tile" † "Akoustolith"

Cathedral of The Madeleine, Salt Lake City
John T. Comes, Pittsburgh, Architect
Johns-Manville Acoustical Correction installed in ceiling panels

fining the sound in some degree to the lower portion of the auditorium. In this way by intensifying the sound reaching the audience, it has its maximum effect, rather than in the slight reduction in reverberation. The best form of sounding-board is a plane surface, hung horizontally near the speaker's head, and of as large extent as is consistent with appearance, the object being to subtend as large an angle as possible at the speaker's mouth. The use of parabolic sounding-boards is to be deplored, as they not only produce unpleasant focusing effects but are also most unsightly. In any case, the slight advantage to be gained by the use of a sounding-board hardly compensates for its expense and appearance.

EFFECTS OF REVERBERATION

The phenomenon of reverberation, besides causing overlapping of syllables with consequent blurring, also prolongs and intensifies any sounds entering from outside or caused by shuffling of feet, coughing, or general restlessness on the part of an audience. The noise from such sources may, in a reverberant room, be entirely sufficient to obliterate a speaker's voice. This is another reason for reducing the reverberation, even though under quiet conditions the speaker can be heard with a fair degree of comfort.

In the case of offices and banking-rooms, especially those of modern construction, the accumulation of sound energy, due to the reverberation of noises from typewriters, adding machines, telephone bells and the like, is so great as not only to be annoying but actually responsible for nervous fatigue and loss of efficiency of the employees. The same phenomenon is also to be observed in restaurants, corridors of public buildings, and similar places. An astonishing degree of quiet can be produced in all such cases by suitable absorptive treatment. Not only is the sound generated in such rooms lessened in intensity to a marked degree, but also that coming through doors and windows, such as the

Chapel, Leland Stanford, Jr., University, Palo Alto, California
Ward & Blohme, San Francisco, Architects
Johns-Manville Acoustical Correction installed in ceiling panels

noise of traffic. A few decades ago such problems commanded but little attention, but modern office machinery and the hard and non-absorptive materials used in fireproof construction have conspired to make the ordinary business office almost as noisy as the proverbial boiler-shop. The increase in errors and the loss of efficiency on the part of the clerical force due to this nerve-shattering racket are facts now being considered by the welfare departments of many of the most progressive business houses.

ECHO

While reverberation is doubtless the most frequent and easily recognized acoustical defect, yet there are other phenomena which may be quite as troublesome, chief among these being echo and interference.

Echo is due to reflection from those surfaces whose contour and arrangement are such as to bring the sound waves to a focus. If the source of sound is short and sharp, and if the difference in path between the reflected and direct waves is sufficiently great, the image produced by the reflected waves appears as a distinct repetition of the original sound. If, however, the difference of path is such that the direct and reflected waves are not separated but overlap on reaching the ear, or if the contour of the reflecting surfaces is such as to produce a blurred and not a sharp focus, confusion is created at that point and hearing made difficult. Such effects are purely local in their character and are not general throughout the auditorium as in the case of reverberation. They, in common with true interference phenomena, are responsible for the "dead spots" of which complaints are so often heard.

Echo of both types is caused in a large degree by curved surfaces such as domes, vaults, coves, pendentives, and warped areas. It can often be eliminated by due care in design, either by proper choice of curvature or by deep coffering. Sometimes a special form of absorptive treatment becomes necessary, the absorbent areas being so distributed as to produce half-

wave phase differences between different portions of the reflected wave, thus causing destructive interference at the focal point.

RESONANCE AND INTERFERENCE

Distinct from the reflection phenomena thus far considered, there exist more complex sources of difficulty which may, in general, be classed under the heads of resonance and interference. By resonance we mean the sympathetic vibration of the body of air within a room in response to some definite pitch. Its effect is to magnify the intensity of the given sound, so that the latter is thrown into relief against all other tonalities, thus producing an unbalanced effect on musical values. It is frequently encountered in organ chambers, and sometimes even in the auditoriums themselves.

A more frequent source of trouble is to be found in difficulties arising from interference. When a sustained tone of constant pitch is produced in a room, the waves reflected from various surfaces meet one another and the oncoming wave in various phase relations, producing points of maximum or minimum loudness, according as the waves meet in the same or opposite phases. Such regions may be readily observed in a church by walking about the auditorium while a single note is sustained on the organ. The points of maximum loudness will shift their location as the pitch of the note is changed, and this becomes an important factor for consideration in the proper voicing of an organ. Such effects produce, as a rule, but little disturbance for speech, but may be very disturbing for music whenever tones are sustained for more than one-tenth of a second. The effects are complex and require individual study in every case which arises.

In résumé, the acoustical quality of an auditorium depends on shape, size, and material. If two of these three factors are determined, the desired acoustical result can be secured only by correspondingly adapting the third. In the completed building, or with plans in which the form is fully determined by other considerations, the adjustment must be by the material, its quality, and its efficient position.

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